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THE GEOGRAPHICAL CYCLE IN AN ARID CLIMATE

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Normal and special cycles.—The scheme of the geographical cycle is usually developed with respect to a land surface under ordinary climatic conditions, not so dry but what all basins overflow and all parts of the surface have continuous drainage to the sea, nor so cold but what the snow of winter all disappears in summer. The term "normal climate" has been applied to such conditions, and "normal cycle" to the scheme that embodies them. It is chiefly this scheme that I have elsewhere treated on various occasions (*a*, *b*, *c*, *h*).[1]

The general scheme of the geographical cycle needs adaptation to two special climates: one, glacial; the other, arid. The glacial cycle received brief attention in one of my papers (*d*) five years ago, but now needs supplement in view of the later studies by Richter, de Martonne, Lawson, and others, as to the forms of glaciated mountains, and in view of the theory announced by Gilbert that glaciers are not buoyed up while they rest on the sea bottom, and that they may therefore erode their channels deep below sea-level. The arid cycle has not been considered as a whole, although special studies of desert conditions have been made by various observers, notably by Walther. The following general considerations are based on the work of others as well as on my own observations in the arid regions of the western United States and of western Asia; they are presented for the most

[1] See list of references at the end of this article.

part in an intentionally and avowedly deductive manner, but they are checked by facts from stage to stage. My especial indebtedness to Passarge is stated below.

The arid climate.—The essential features of the arid climate, as it is here considered, are: so small a rainfall that plant growth is scanty, that no basins of initial deformation are filled to overflowing, that no large trunk rivers are formed, and hence that the drainage does not reach the sea.

The agencies of sculpture and their opportunities for work in arid regions are peculiar in several respects. The small rainfall and the dry air reduce the ground water to a minimum. In its absence, weathering is almost limited to the surface, and is more largely physical than chemical. The streams are usually shorter than the slopes, and act as discontinuously at their lower as at their upper ends. The scarcity of plant growth leaves the surface relatively free to the attack of the winds and of the intermittent waters. Hence, in the production of fine waste, the splitting, flaking, and splintering of local weathering are supplemented rather by the rasping and trituration that go with transportation than by the chemical disintegration that characterizes a plant-bound soil.

No special conditions need be postulated as to the initiation of the arid cycle. The passive earth's crust may be (relatively) uplifted and offered to the sculpturing agencies with any structure, any form, and any altitude, in dry as well as in moist regions.

Initial stage.—Let consideration be given to an uplifted region of large extent over which an arid climate prevails. Antecedent rivers, persisting from a previous cycle against the deformations by which the new cycle is introduced, must be rare, because such rivers should be large, and large rivers are unusual in an arid region. Consequent drainage must prevail. The initial slopes in each basin will lead the wash of local rains toward the central depression, whose lowest point serves as the local baselevel for the district. There will be as many independent centripetal systems as there are basins of initial deformation; for no basin can contain an overflowing lake, whose outlet would connect two centripetal systems: the centripetal streams will not always follow the whole length of the centripetal slopes; most of the streams of each basin system will wither away after descending from

the less arid highlands to the more arid depressions. Each basin system will therefore consist of many separate streams, which may occasionally, in time of flood or in the cooler season of diminished evaporation, unite in an intermittent trunk river, and even form a shallow lake in the basin bed, but which will ordinarily exist independently as disconnected headwater branches.

Youthful stage —In the early stage of a normal cycle the relief is ordinarily and rapidly increased by the incision of consequent valleys by the trunk rivers that flow to the sea. In the early stage of the arid cycle the relief is slowly diminished by the removal of waste from the highlands, and its deposition on the lower gentler slopes and on the basin beds of all the separate centripetal drainage systems. Thus all the local baselevels rise. The areas of removal are in time dissected by valleys of normal origin: if the climate is very arid, the uplands and slopes of these areas are either swept bare, or left thinly veneered with angular stony waste from which the finer particles are carried away almost as soon as they are weathered; if a less arid climate prevails on the uplands and highlands, the plants that they support will cause the retention of a larger proportion of finer waste on the slopes. The areas of deposition are, on the other hand, given a nearly level central floor of fine waste, with the varied phenomena of shallow lakes, playas, and salinas, surrounded with graded slopes of coarser waste. The deposits thus accumulated will be of variable composition and, toward the margin, of irregular structure. The coarser deposits will exhibit a variety of materials, mechanically comminuted, but not chemically disintegrated, and hence in this respect unlike the less heterogeneous deposits of humid climates from which the more easily soluble or decomposable minerals have been largely removed. The finer deposits will vary from sand and clay to salt and gypsum. The even strata that are supposed to characterize lake deposits may follow or precede irregular or cross-bedded strata, as the lake invades or is invaded by the deposits of streams or winds. While many desert deposits may be altogether devoid of organic remains, others may contain the fossils of land, stream, or lake organisms.

The Basin Range province of the western United States gives examples of dissected mountains from which descend many withering streams that belong to separate drainage systems of the kind

above described, and of basins aggraded with the waste from the dissected mountains. Trunk streams are rare. The initial relief has been decreased, although the basin floors are from 3,000 to 5,000 feet above sea-level. Persia and Tibet give further illustrations of the same relation. In the latter region the intermont basins often contain saline lakes; but the stage of development there reached is not yet clear, because the origin of the ranges and basins is not, as a rule, considered by Tibetan explorers. It should not, however, be inferred that the separation of the many drainage systems in regions such as those of Persia and Tibet is the result of any special peculiarity in the initial deformation of the surface, essentially unlike the deformation of other regions of normal climate, where large unified drainage systems are the rule. The latter regions may initially have had as many basins of deformation as the former, but the more plentiful rainfall of normal climate has enabled their rivers to cut down the basin rims. This principle has been pointed out by Penck (*a*, p. 87; *b*, p. 159) and others. The initial relief may be of coarse pattern, as in central Asia, where the vast aggraded plains of eastern and western Turkestan are separated by a broadly uplifted and deeply dissected mountainous area; or of finer pattern, as in the Basin Range province just mentioned, where many small ranges separate nearly as many small basins. The progress of evolution through the cycle, and the arrangement of forms at successive stages, will be much affected by these unlike initial conditions.

Streams, floods, and lakes are the chief agencies in giving form to the aggraded basin floors, as well as to the dissected basin margins in the early stages of the cycle; but the winds also are of importance: they do a certain share of erosion by sand-blast action; they do a more important work of transportation by sweeping the granular waste from exposed uplands and depositing it in more sheltered depressions, and by raising the finer dust high in the air and carrying it far and wide before it is allowed to settle. Wind-action is, moreover, peculiar in not being guided by the slopes or restrained by the divides which control streams and stream systems. It is true that the winds, like the streams, tend in a very general way to wear down the highlands and to fill up the basins; but sand may be drifted uphill—dunes may be seen climbing strong slopes and escarpments

in Arizona and Oregon—while fine dust carried aloft in whirlwinds and dust-storms is spread about by the upper currents with little regard to the slopes of the land surface far below. Sand may be drifted, and dust may be in this way carried outside of the arid region from which it was derived. Wind-erosion may, furthermore, tend to produce shallow depressions or hollows; for the whole region is the bed of the wind, and is therefore to a certain extent analogous to the bed of a river, where hollows are common enough; but in the early stages of the cycle in a region where the initial relief was strong, the action of the wind is not able to make hollows on the original slopes that are actively worked upon, and for a time even steepened, by streams and floods. Hence in the youthful stage wind-blown hollows are not likely to be formed.

It is important to notice that a significant, though small, share of wind-swept or wind-borne waste may be carried entirely outside of or "exported" from an arid region. It may be deposited on neighboring lands, where it will be held among the grass of a less arid climate, as long ago suggested by Richthofen; it may even be held down on coastal lands by the dew, as has been suggested for certain districts in Morocco by Fischer; it may fall into the sea, as is proved by the sand that gives a ruddy tinge to the sails of vessels in the Atlantic to leeward of the Sahara, and by the sand grains that are dredged up with true pelagic deposits from the bottom of that part of the Atlantic. It may therefore be expected that the progress of erosion and waste exportation in a desert region should be associated with the deposit of fine waste, as in loess sheets, on the neighboring less arid regions, especially down the course of the prevailing winds. In regions of weak and variable winds the process of sand and dust exportation must be extremely slow; in regions of steady winds it must still be vastly slower than the ordinary rate of waste removal in young or mature regions of plentiful rainfall and normal rivers. Yet it is by this slow process of exportation that the mean altitude of an arid region, such as is here considered, will be continually decreased; hence the earlier stages of the arid cycle are expectably longer than the corresponding stages of the normal cycle.

In the normal cycle the youthful stage is characterized by the headward growth of many subsequent streams, chiefly along belts

of weak structures that are laid bare on the valley sides of the larger consequent streams. In the arid cycle subsequent streams have a smaller opportunity for development; first because all the belts of weak structure under the basin deposits are buried out of reach; second, because, in the absence of deep-cutting trunk rivers, many belts of weak structure are but little exposed. In so far, however, as the highlands are dissected by their headwater consequent streams, subsequent branches may grow out and diversify the slopes and rearrange the drainage.

Mature stage.—Continued erosion of the highlands and divides, and continued deposition in the basins, may here and there produce a slope from a higher basin floor across a reduced part of its initial rim to a lower basin floor. Headward erosion by the consequent or subsequent streams of the lower basin will favor this change, which might then be described as a capture of the higher drainage area. Aggradation of the higher basin is equally important, and a change thus effected might be described as an invasion of the lower basin by waste from the higher one; this corresponds in a belated way to the overflow of a lake in a normal cycle. There may still be no persistent stream connecting the two basins, but whenever rain falls on the slope that crosses the original divide, the wash will carry waste from the higher to the lower basin. Thus the drainage systems of two adjacent basins coalesce, and with this a beginning is made of the confluence and integration of drainage lines which, when more fully developed, characterize maturity. The intermittent drainage that is established across the former divide may have for a time a rather strong fall; as this is graded down to an even slope, an impulse of revival and deeper erosion makes its way, wave-like, across the floor of the higher basin and up all its centripetal slopes. The previously aggraded floor will thus for a time be dissected with a bad-land expression and then smoothed at a lower level; the bordering waste slopes will be trenched and degraded. At the same time, the lower basin floor will be more actively aggraded. If there is a sufficient difference of altitude between the two basins, all the waste that had been, in a preliminary or youthful view of the case, gathered in the higher basin, will in time be transferred to the lower basin; and thus a larger relation of drainage lines, a longer distance of intermittent

transportation, a more continuous area of bed-rock in the higher areas, and a more general concentration of waste in the lowest basins will be established. The higher local baselevels are thus, by a process of slow, inorganic natural selection, replaced by a smaller and smaller number of lower and lower baselevels; and with all this go a headward extension of graded piedmont slopes, a deeper dissection of the highlands, and a better development of their subsequent and adjusted drainage. The processes of drainage adjustment are, however, at the best, of less importance here than in the normal cycle, because of the absence of main valleys, deep-cut by trunk rivers, and the resulting deficient development of deep-set subsequent streams, as has already been suggested.

Some changes of this kind have probably taken place in the Basin Range province of Utah and Nevada, but more field work will be needed before they can be safely pointed out. Indeed, it seems to be the case that certain changes of an opposite kind have taken place; the long intermont troughs appear to be here and there subdivided into separate basins by the undue growth of certain detrital fans where large valleys have been opened in the neighboring ranges; but this condition of things will pass when the mountains are worn lower and the waste is discharged from them less actively.

As the coalescence of basins and the integration of stream systems progress, the changes of local baselevels will be fewer and slower, and the obliteration of the uplands, the development of graded piedmont slopes, and the aggradation of the chief basins will be more and more extensive. The higher parts of the piedmont slopes may be rock-floors, thinly and irregularly veneered with waste, as has been described by Keyes for certain basins (bolsons) in New Mexico; here, as well as upon the aggraded slopes and plains, sheet-flood action will prevail, as explained by McGee. The area occupied during early maturity by the three different kinds of surface—dissected highlands or mountains, graded piedmont slopes of rock or waste, and aggraded central plains with playas, salinas, or lakes—will depend on the initial relief, on the rock structure and its relation to desert weathering, on the percentage of material exported by the winds, and on the climate itself.

It is worth noting that, although the activity of streams and floods

decreases with the decrease of relief and of slope, the activity of the winds is hardly affected as maturity advances. The winds do not depend on the gradient of the land surface for their gravitative acceleration; they may blow violently and work efficiently on a level surface. Whirlwinds are, indeed, most active on true plains. It may be that smooth plains are never swept by winds so violent as the blasts which attack highlands and mountains; but it is probable that the effective action of the winds is greater on a generally plain surface than on one of strong relief, where the salient ridges and peaks consist largely of firm rock, and where the loose waste is sheltered in re-entrant valleys. Moreover, it is in very great part on the plains that the winds of ordinary strength drift the sand about, and from the plains that whirlwinds and dust-storms raise the finest waste high enough for exportation. It may therefore be concluded that the work of the winds is but little, if any, impaired by the general decrease of relief that characterizes advancing maturity; and hence that their relative importance increases. Moreover, the scanty rainfall of an arid region will be decreased as its initial highlands, which originally acted as rain-provokers, are worn down; hence, as the relief weakens, the winds will more and more gain the upper hand in the work of transportation. It is conceivable that the rate of exportation of sand and dust by the winds in maturity and all the later stages of an arid cycle is more rapid than the removal of fine soil, partly or largely in solution, from a plant-covered peneplain in the later stages of a normal cycle; thus the slower work of the earlier stages of an arid cycle may be partly made good by the relatively more active work in the later stages.

As the processes thus far described continue through geological periods, the initial relief will be extinguished even under the slow processes of desert erosion, and there will appear instead large, rock-floored plains sloping toward large waste-floored plains; the plains will be interrupted only where parts of the initial highlands and masses of unusually resistant rocks here and there survive as isolated residual mountains. At the same time, deposits of loess may be expected to accumulate in increasing thickness on the neighboring less arid regions. The altitude at which the desert plain will stand is evidently independent of the general baselevel—or sea-level—and

dependent only on the original form and altitude of the region, and on the amount of dust that it has lost through wind transportation.

The most perfect maturity would be reached when the drainage of all the arid region becomes integrated with respect to a single aggraded basin-baselevel, so that the slopes should lead from all parts of the surface to a single area for the deposition of the waste. The lowest basin area which thus comes to have a monopoly of deposition may receive so heavy a body of waste that some of its ridges may be nearly or quite buried. Strong relief might still remain in certain peripheral districts, but large plain areas would by this time necessarily have been developed. In so far as the plains are rock-floored, they would truncate the rocks without regard to their structure.

There is no novelty in the idea that a mountainous region of interior drainage may be reduced to a plain by the double process of wearing down the ranges and filling up the basins, and that the plain thus formed, consisting partly of worn-down rock and partly of built-up waste, will not stand in any definite relation to the general baselevel of the ocean surface; yet the idea has seldom been applied in the interpretation of uplifts by the physiographic method. In the case of the plateaus that are now trenched by the Colorado river in northern Arizona, for example, it has usually been tacitly postulated that the baselevel with respect to which they were widely denuded in the pre-canyon cycle was the normal baselevel of the ocean, and from this postulate it has been argued that the cycle of canyon erosion was introduced by a strong uplift. My own opinion has agreed with that of Dutton and others in this respect. Yet it is not today easily demonstrated that the Arizona plateaus had exterior drainage at the time of their wide denudation; and until exterior drainage is shown to have obtained, the altitude of the plateau region during its denudation must remain uncertain. There are, however, several facts which point to the correctness of the generally accepted view: the course of the Colorado river through the Kaibab cannot easily be explained as having originated in the present cycle; it appears to have been established earlier; and it is doubtful whether there are late Tertiary basin deposits within the desert area, or wind-carried sand and loess deposits in the area to the eastward (leeward) of

sufficient volume to represent the great volume of material removed in the degradation of the plateaus.

In the case of truncated uplands elsewhere—that is, uplands whose surface truncates their structure, as in the central plateau of France—it is generally a tacit postulate, if not a proved conclusion, that the climate during their truncation was not arid, and hence it is inferred that they were worn down as peneplains with respect to normal baselevel, and that they have been uplifted since; this aspect of the problem will be considered farther on. In the meantime, there is another aspect of erosion in arid regions which, to my knowledge, has not, until recently, received attention.

The beginning of old age.—During the advance of drainage integration the exportation of wind-borne waste is continued. At the same time, the tendency of wind-action to form hollows wherever the rocks weather most rapidly to a dusty texture would be favored by the general decrease of surface slopes, and by the decrease of rainfall and of stream-action resulting from the general wearing-down of the highlands. Thus it may well happen that wind-blown hollows should be produced here and there, through the mature and later stages of the cycle, and that they should even during early maturity interfere, to a greater or less degree, with the development of the integrated drainage, described above. In any case, it may be expected that wind-blown hollows would in late maturity seriously interfere with the maintenance of an integrated drainage system. Thus it appears that, along with the processes which tend toward the mature integration of drainage, there are other processes which tend toward a later disintegration, and that the latter gain efficiency as the former begin to weaken. A strong initial relief of large pattern, a quality of rock not readily reducible to dusty waste, and an irregular movement of light winds might give the control of sculpture to the intermittent streams through youth and into maturity; in such a case maturity might be characterized by a fully integrated system of drainage slopes, with insignificant imperfections in the way of wind-blown hollows. In a second region an initial form of weaker relief, a quality of rock readily reducible to dust, and a steady flow of strong winds might favor the development of wind-blown hollows or basins, and here the process of drainage disintegration would set

in relatively early and prevent the attainment of mature drainage integration. In any case, as soon as the process of drainage disintegration begins to predominate, maturity may be said to pass into old age.

This feature of the arid cycle has no close analogy with the features recognized in the normal cycle. In the latter case, the drainage systems of maturity tend on the whole to persist, even though the streams weaken and wander somewhat—and according to theory lose some of their adjustments—in very advanced old age; in the former case, as old age advances, the integrated and enlarged drainage systems of maturity are broken up into all manner of new and local, small and variable, systems. The further results of drainage disintegration in the later stages of the cycle are even more peculiar.

Leveling without baseleveling.—The later consequences of erosion in an extensive arid region have been, as far as my reading goes, first and recently stated by Passarge, in connection with his studies of the arid regions of South Africa, as is more fully indicated below.

As the dissected highlands of maturity are worn down, the rainfall decreases, and the running streams are weakened and extinguished; thus, as has been suggested above, the winds in time would appear to gain the upper hand as agents of erosion and transportation. If such were the case, it would seem that great inequalities of level might be produced by the excavation of wide and deep hollows in areas of weak rocks. As long as the exportation of wind-swept sand and of wind-borne dust continued, no easily defined limit would be found for the depth of the hollows that might thus be developed in the surface, for the sweeping and lifting action of the wind is not cotrolled by any general baselevel. In an absolutely rainless region there appears to be no reason for doubting that these abnormal inequalities of surface might eventually produce a strong relief in a still-standing land of unchanging climate; but in the actual deserts of the world there appears to be no absolutely rainless region; and even small and occasional rainfalls will suffice, especially when they occur suddenly and cause floods, as is habitual in deserts, to introduce an altogether different régime in the development of surface forms from the rock hills and hollows which would prevail under the control of the winds alone. The prevailing absence of such hill-and-hollow forms, and the

general presence of graded wadies and of drainage slopes in desert regions, confirm this statement.

As soon as a shallow wind-blown hollow is formed, that part of the integrated drainage system which leads to the hollow will supply waste to it whenever rain falls there; the finer waste will be blown away, the coarser waste will accumulate, and thus the tendency of the winds to overdeepen local hollows will be spontaneously and effectively counteracted. As incipient hollows are formed in advancing old age, and the maturely integrated drainage system disintegrates into many small and variable systems, each system will check the deepening of a hollow by wind-action; hence no deep hollow can be formed anywhere, so long as occasional rain falls.

It is conceivable that, in some special cases, there might be a peculiar balance of the various factors involved which would result in the development of wind-carved hills and hollows, even if the region were not absolutely rainless. The occurrence of permeable sandstones might favor such a result, because the rain falling on them would sink into the ground instead of running off of it, while fine grains weathered from the sandstone would be disposed of by the winds. But for the present no desert sandstone region with hills and hollows is known while such regions with hills and valleys are common. Hence it must be inferred that even in sandstone deserts the occasional rains suffice to wash the surface and to prevent the formation of anything more than very shallow depressions.

As the drainage becomes more and more disintegrated, and the surface of the plain is slowly lowered, rock masses that most effectually resist dry weathering will remain as monadnocks—*Inselberge*, as Bornhardt and Passarge call them in South Africa. At the same time, the waste will be washed away from the gathering grounds of maturity and scattered in the shallow hollows that are formed here and there by the winds as old age approaches. The removal of the basin deposits by the winds may be delayed where the hygroscopic action of saline clays keeps the surface firm; but wherever the integrated centripetal slopes are locally reversed by the hollowing action of the wind, some of the central deposits will be washed back again and exposed to renewed search for fine material by the wind,

and thus a larger and larger part of the central waste will be redistributed and exported. As there is no relation of parts in the winds analogous to that of small branch and large trunk streams in river systems, the surface eroded by the winds need not slope toward any central area, but may everywhere be worn down essentially to the same level. The surface ever wearing down, the waste ever washed irregularly about by the variable disintegration of the drainage system and continually exported by the winds, a nearly level rock-floor, nowhere heavily covered with waste, and everywhere slowly lowering at the rate of sand and dust exportation, is developed over a larger and larger area; and such is the condition of quasi-equilibrium for old age. At last, as the waste is more completely exported, the desert plain may be reduced to a lower level than that of the deepest initial basin; and then a rock-floor, thinly veneered with waste, unrelated to normal baselevel, will prevail throughout—except where monadnocks still survive. This is the generalization that we owe to Passarge; it seems to me secondary in value only to Powell's generalization concerning the general baselevel of erosion. So long as the sea is held out, it would seem that a desert surface might be worn even below sea-level, as certain writers have pointed out in a general way (Penck, *b*, p. 167); but that such a desert should persistently maintain a plain surface while it is slowly worn lower and lower is a surprising result of deduction. Little wonder that an understanding of the possible development of rock-floored deserts of this kind, independent of baselevel, was not reached inductively in western America; for there has been so much disturbance in the way of fracture and uplift in that region during Mesozoic, Tertiary, and Quaternary time that the attainment of arid old age has not been permitted; but that the problem was not solved deductively by the present generation of American physiographers before it was encountered and solved by others in Africa serves to show how insufficient still is the use of the deductive method among us.

Passarge writes that his attention has been called to the difficulty of explaining the vast plain surfaces of South Africa by wind-action, because the wind has no baselevel of erosion, and it therefore can and must excavate considerable hollows in rock areas whose waste it can easily remove. He adds that this difficulty disappears as soon

as rain works with the wind, since the rain constantly seeks to wash waste into the hollows formed by the wind, whose tendency to make hollows is thereby counteracted.[1]

The verity of the arid cycle.—The deductive method by which most of the preceding paragraphs are characterized may be regarded by some readers as reaching too far into the field of untestable speculation. It is true that the examples of observed forms, by which the deduced forms of every stage should be matched, are as yet not described in sufficient number; but this may be because desert regions have not yet been sufficiently explored with the principles herein set forth—particularly Passarge's law—in mind. On the other hand, the examples of desert plains in South Africa, described by Passarge as plains of the Bechuana (Betschuana) type, suffice to show that the stage of widespread desert-leveling has actually been reached in that region, and thus justify all the earlier stages; for, however many land movements may have interrupted the regular progress of preceding cycles, the occurrence of widespread rock plains proves that at least the present cycle of arid erosion has been long continued without disturbance.

The levelness of the plains over wide areas is especially emphasized. Isolated mountains rise above the plains; and the combination of the two unlike forms is described under the term *Inselberglandschaft*, suggested by Bornhardt. Passarge states that these desert plains are not undulating with low hills, but true plains of great extent, from which the isolated residual mountains rise like islands from the sea. The residuals may be low mounds, only a few meters high, or lofty mountain masses, rising several thousand meters above the plains. The plain surrounds the steep slope of the mountains with a table-like evenness; there is no transitional belt of piedmont hills, and no intermediate slope (*b*, p. 194). The mountains consist of resistant rocks, such as granite, diorite, gabbro, quartzite, etc.,

[1] "Herr Geheimrath v. Richthofen machte mich auf die Schwierigkeit aufmerksam, die riesigen, faktisch ebenen Flächen durch Windwirkung zu erklären, dafür der Wind kein 'baselevel of erosion' bestände und er aus Gestein, das sich leicht abtragen lässt, bedeutende Vertiefungen ausarbeiten könne und müsse. Diese Schwierigkeit fällt fort, sobald spülender Regen mitarbeitet. Denn dieser sucht die durch den Wind geschaffenen Vertiefungen beständig mit Schutt—Sand, Lehm, etc.—auszufüllen, arbeitet also dem Wind entgegen" (Passarge, *b*, p. 208).

granite being the most frequent; the plains are of more easily eroded rocks, such as gneiss, schists, slates, sandstones, and limestones. The bedding of the rocks is not flat, but disturbed; the plain therefore truncates the rock structures. The rocks are not deeply decomposed, but are relatively fresh. The products of weathering are usually spread as a thin veneer on the plain; the waste does not lie in place, on the rocks from which it was weathered, but has been drifted about by wind and flood, and has gathered in slight depressions. The waste veneer increases the smoothness of the plain, but the rock surface is also a plain, as may be seen in the edge of water channels, as well as where the veneer is absent (*b*, p. 195). Neighboring areas contain extensive deposits of irregular strata, whose composition and want of fossils indicate their desert origin, as will be referred to again below. Various additional details are given, with the conclusion as above quoted: these rock-floored plains are not uplifted peneplains, but are the product of desert erosion unrelated to normal baselevel, in which occasional water-action has co-operated with more persistent wind-action.

The scheme of the arid cycle thus seems to be as well supported by appropriate facts as is the scheme of the normal cycle; it is, indeed, in one respect even better supported, for while the arid African plains are examples of old desert plains now growing still older, it is difficult to point out any large peneplain that still stands close to the baselevel with respect to which it was worn down.

Contrasted consequences of normal baseleveling and desert-leveling.—While the theory of marine planation was in vogue, it was customary to interpret all evenly truncated uplands—that is, uplands whose surface truncates their rock-structure—as uplifted plains of marine abrasion, more or less dissected since they were uplifted. When the efficacy of subaerial erosion was recognized, it became equally customary to interpret truncated uplands as once baseleveled and afterward uplifted peneplains. If Passarge's views be now accepted, it follows that no truncated uplands should, without further inquiry, be treated as having been eroded when their region had a lower stand with respect to baselevel; the possibility of their having been formed during an earlier arid climate as desert plains, without regard to the general baselevel of the ocean, must be considered and excluded before baseleveling and uplift can be taken as proved.

It may at first appear sufficient to say that high-standing desert plains can have been made only in those regions which are now desert, but this easy solution of the problem is hardly convincing. Climatic changes are known to have occurred in the past, and inasmuch as they did not all affect areas in a way that is sympathetic with the present arrangement of the zones, the possibility of a former different distribution of deserts from that which now occurs seems to be open. Pleistocene climatic changes of the glacial kind were so modern and short-lived that they have little bearing on the possibility of earlier climatic changes of another order. The more ancient records of glaciation are so distributed as to demand significant rearrangement of the present climatic conditions. The existing deserts are, moreover, of two kinds with respect to cause: some deserts, like those of Africa and Australia, are arranged chiefly with respect to the trade-wind belt; other deserts, like those of central Asia and the southwestern United States, are dependent for the most part on the extent and configuration of the surrounding highlands. When we go back as far as Cretaceous time, it should only be by evidence and not by assumption that we are led to regard a truncated upland of that date as having been baseleveled during a cycle of normal climate and afterward uplifted and dissected, instead of having been leveled above baselevel during a cycle of arid climate, and dissected in consequence of a change to a normal climate. A century ago demonstrated movements of the earth's crust were matters of astonishment; witness the surprise then felt at the discovery of fossilized marine shells in some of the loftier Alpine ranges. Today the crust is raised and lowered on the evidence of dissected peneplains, as in the Appalachian region, without exciting remark; it is now the shifting of climatic conditions that would cause dissenting surprise. It is difficult to determine how far such surprise is well founded, and how far it simply reflects the fashion of our time. Even if the climatic zones have always belted the earth as they do now, the desert areas that depend on the configuration of land and water, and of highlands and lowlands, have certainly varied through the geological ages. It is therefore desirable, wherever the question of "uplifted and dissected peneplains" is raised, to scrutinize it carefully, and to determine, if possible, whether it is really the attitude

of the earth's crust or the condition of climate that has been changed. It is likewise important to scrutinize desert plains, now standing above baselevel, to see if they may not have been formed normally as lowland plains of erosion and afterward uplifted. It is therefore necessary to inquire into these features by which baseleveled peneplains and rock-floored desert plains may be distinguished, even though the former may be uplifted with a change to an arid climate, or though the latter may be depressed with a change to a humid climate.

Passarge holds the opinion that the plains of the *Inselberglandschaft* are smoother than any peneplain can be; for he describes the desert plains as true plains, not as gently undulating surfaces. He states that water is not competent to produce such plains; its power of erosion works chiefly downward, and only by exception laterally; and he concludes that, although long-continued normal erosion may produce a peneplain—that is, a low, undulating hilly surface—it nevertheless cannot produce a surface like that of the plains in the *Inselberglandschaft.*[1] But, however difficult it may be to wait, in imagination, through the ages required to wear a low hilly region down to less and less relief by the weakened processes of weather and water erosion in the latest stages of the normal cycle, there are certainly some truncated uplands, ordinarily taken to be uplifted peneplains, whose interstream uplands are astonishingly even, and whose surface must have been, before dissection, very nearly plain over large areas; hence it does not seem to me altogether certain that a greater and a less degree of flatness can be taken to distinguish the two classes of plains.

A plain of erosion lying close to sea-level in a region of normal climate, and therefore traversed by rivers that reach the sea, but that do not trench the plain, might conceivably be a depressed desert plain standing long enough in a changed climate to have become cloaked with local soils; but it is extremely unlikely that the depression of a desert plain could place it so that it should slope gently to the

[1] Wasser ist nicht imstande solche Ebene zu erodieren. Seine Erosionskraft wirkt hauptsächlich in die Tiefe, nur ausnahmsweise in die Breite. . . . . Bei sehr lang andauernder Abtragung kann wohl eine 'Peneplain' zustande kommen, d. h. ein flaches welliges Hügelland, aber keine Fläche, wie die Ebenen der Inselberglandschaften" (*b*, p. 196).

seashore, and that its new-made rivers should not dissect it, and that there should be no drifted sands and loess sheets on adjoining areas, and no signs of submergence on neighboring coasts. An untrenched plain of erosion in such an attitude would be properly interpreted as the result of normal processes, long and successfully acting with respect to normal baselevel. There would therefore appear to be no serious danger of confusing an actual peneplain of normal origin, still standing close to baselevel, with a depressed plain of desert origin. For the reasons above given I am not disposed to follow Passarge in the suggestion that the old land mass of Guiana may be an *Inselberglandschaft* in the process of destruction. He cites it as a flat, gently undulating surface of gneiss, above which rise knobs and mountains of granite; the divides are so low that one may pass in canoe between the headwaters of the Orinoco and Amazon systems (*b*, p. 194). Until further details are given, it would seem appropriate to regard this region, like the interior of Brazil to which Lapparent refers (*a*, p. 148), as an example of a normal peneplain, not raised so as to be attacked by its rivers.

In the same way a high-standing plain of erosion in a desert region might be possibly explained as an evenly uplifted peneplain whose climate had in some way been changed from humid to arid, whose deep weathered soils had been removed and replaced by thin sheets of stony, sandy, or saline waste, and whose residual reliefs had been modified to the point of producing shallow basins. But in this case there should be some indications of recent uplift around the margin of the area, either in the form of uplifted marine formations whose deposition was contemporaneous with the erosion of the peneplain, or in the form of fault-escarpments separating the uplifted from the non-uplifted areas. Moreover, it is extremely unlikely that the uplift of an extensive peneplain could place it in so level a position that it should not suffer dissection even by desert agencies; hence a high-standing desert plain is best accounted for by supposing that it has been leveled in the position that it now occupies. According to Passarge, there are no sufficient indications of elevation associated with the South African desert plains, and their explanation as the product result of long-continued desert erosion in a still-standing region would therefore seem to be assured.

Whether an appropriate deposit of wind-borne waste is to be found on neighboring regions is not yet made clear.

It should not, however, be overlooked that there is some danger of misreading the history of a depressed desert plain which has been by a moderate amount of normal weathering and erosion transformed into a normal peneplain; and of an uplifted peneplain which has been by a moderate amount of arid weathering and erosion transformed into a typical desert plain; the danger of error here is similar to that by which a peneplain, wave-swept and scoured during submergence, might be mistaken for a normal plain of marine abrasion. The consequences of error in these cases of actual plains are, however, not so serious as in those which may arise in connection with dissected plains; for this class of forms is of common occurrence, and mistakes in explaining their origin as uplifted peneplains or as changed-climate desert plains might therefore be of frequent and widespread occurrence. It is therefore desirable to search out those features by which normal peneplains, uplifted and dissected, may be distinguished from desert plains, dissected after a change to humid climate.

If a normal peneplain be uplifted, its already adjusted streams will carry their adjustments still farther in the new cycle. The high degree of adjustment of streams to structures in the Pennsylvania Appalachians and in the mediæval coastal plain of central England therefore suggests that the former surface of truncation, beneath which the present lower lands have been etched out, was a normal peneplain, uplifted. If a normal peneplain be tilted, its depressed part will soon be submerged and covered with marine deposits; and this part may, by later uplift, be associated with the elevated and dissected part. The marine deposits of our Atlantic and Gulf coastal plain, certain basal strata of continental origin excepted, seem to lie upon a depressed part of the Appalachian peneplain, and thus confirm the evidence of normal baseleveling derived from the adjusted drainage of the uplifted and dissected part of the same peneplain; the basal strata just mentioned contain fossil land plants of normal climate and confirm the conclusion. The now dissected uplands of Brittany and of the Ardennes are adjoined or overlapped by marine deposits which give strong suggestion of normal pene-

planation, as shown by Lapparent (*b*). Disturbances of the arid cycle are followed by consequences of other kinds.

Interruptions and modifications of the arid cycle.—A land mass suffering erosion under an arid climate may, as in the normal cycle, suffer interruption in the regular progress of its changes by movement of any kind at any stage of development. If, for example, integration of drainage has advanced so far that the number of original basins is reduced by half, the number may be increased again by renewed deformation; or if the integration of drainage has reached a mature stage, the drainage may be thrown into disorder again by a more or less gentle warping of the region. In all such cases a new cycle may be regarded as having been initiated; its initial forms will be the eroded forms developed during the preceding incomplete cycle, and displaced by the movements through which the preceding cycle was closed. The work of the new cycle, thus initiated, then goes on as before; but with interruptions of this kind we are not here particularly concerned, because they offer no special difficulty of explanation or interpretation.

It is otherwise when interruptions or modifications of the arid cycle occur after old age is well advanced, for the desert plains then developed may, under certain conditions, come to imitate uplifted undissected peneplains, as has already been partly considered in the preceding section.

Uniform uplift or depression, by which a normal peneplain is so immediately and significantly modified, will not interrupt the regular process of degradation on a desert plain in an arid cycle. It is perhaps in part for this reason that actual examples of rock-floored desert plains appear to be more common than actual examples of peneplains. Depression would drown a peneplain, and elevation would cause its dissection; but, unless carried to an extreme, neither of these movements would greatly affect the slow degradation of a desert plain. Unequal movements, whereby a desert plain is warped or slanted, are of more importance and are probably of more common occurrence.

If an old rock-floored desert plain be gently warped or tilted, marine submergence is not likely to follow immediately, but the regular continuation of general degradation will be interrupted. The

patches and veneers of waste will be washed from the higher to the lower parts of the warped surface; the higher parts, having an increased slope, might be somewhat dissected, and would certainly be exposed to more active degradation than before, until they were worn down to a nearly level plain again. The lower parts would receive the waste from the higher parts, and the continuance of this process of concentration would in time cause the accumulation of extensive and heavy deposits in the lower areas. Such deposits will be, as a rule, barren of fossils; the composition, texture, and arrangement of their materials will indicate the arid conditions under which they have been weathered, transported, and laid down; their structures will seldom exhibit the regularity of marine strata, and they may reach the extreme irregularity of sand-dune deposits. If warping continues, the desert deposits may gain great thickness; their original floor may be depressed below sea-level, while their surface is still hundreds or thousands of feet above sea-level.

Passarge gives a number of instances which he groups under the Banda type (*b*, p. 200) that seem to illustrate this phase of the arid cycle, although he ascribes the barren sandstones of this type to a weakening in the activity of the winds, rather than to a tilting of the region. Here the upper parts of monadnocks—*Inselberge*—rise above a broad deposit of barren continental sandstones; the intermont plains, being buried, are matters of interference. Examples of this type are mentioned in West Australia as well as in Africa.

If a change from an arid toward a moister climate causes a drainage discharge to the sea, a dissection of the plain will ensue. The valleys thus eroded cannot expectably exhibit any great degree of adjustment to the structures, because the stream courses will result from the irregular patching together of the pre-existing irregularly disintegrated drainage. This peculiar characteristic, taken together with the absence of neighboring uplifted marine deposits, will probably suffice in most cases to distinguish desert plains, dissected by a change to a moister climate, from peneplains dissected in consequence of upilft; but there still might be confusion with peneplains dissected by superposed streams.

Passarge gives two types of desert plains with a modified climate. The first or Kordofan type (*b*, p. 200) is marked by a slight increase

of rainfall, sufficient to introduce a steppe vegetation, but not sufficient to form rivers that shall reach the sea. In this case the larger residual mountain masses come to be surrounded by washed deposits coarser near the mountain base, finer farther forward, and at last grading into swampy areas with dark rich soil. Such deposits are said to be well developed in Kordofan, where the buried eroded plain between the mountains has been revealed by well borings, and where basins in the buried plain are indicated by certain unusual accumulations of ground water. The second or Adamaua type (*b*, p. 201) includes an example of more abundant rainfall, and therefore exhibits the dissection of what is taken to have been a desert plain with *Inselberge;* but the relation of streams to structures is not mentioned. Finally a Rovuma type (*b*, p. 202) is instanced on the authority of Bornhardt, in which marine Cretaceous strata of moderate thickness lie upon a plain whose erosion is ascribed to pre-existing desert conditions.

Diversion of desert drainage to exterior discharge.—The development of desert plains without regard to normal baselevel is possible only so long as they are interior basins, without drainage discharge to the sea. The maintenance of this essential condition is imperiled by small area, great altitude, no inclosing mountains, strong exterior slopes to the sea, and the occurrence of heavy rainfall on the exterior slopes. A small desert island would have no room for the production of interior basins by the processes of initial deformation, or for their maintenance against the attack of exterior streams. The absence of inclosing mountains around a continental arid region would permit the development of escaping drainage systems, so that when mature integration was reached, it might be developed with respect to normal baselevel, instead of with respect to a local interior baselevel; the Sonoran district of Mexico, as described by McGee, seems to offer examples of this kind. Great altitude of an arid region and strong exterior slopes would give strength to attacking exterior streams, and no advantage to the interior drainage; some of the basins of Tibet have already been invaded by the headwater erosion of Himalayan streams, for here the unfavorable conditions of great altitude in the basins, strong exterior slopes, and heavy exterior rainfall are all combined.

On the other hand, great area, moderate altitude, inclosure by mountain barriers, and small exterior rainfall are favorable to the leveling of interior desert plains; and to these favoring conditions should be added a long geological period of quiet. The greater the area and the less the altitude, the less the opportunity that exterior streams will have to establish relations with the interior streams. The higher the inclosing mountains, the longer the interior region will be left to itself, but the more dust it will have to export before a general rock-floor can be developed; the desert of Gobi offers an example of this kind, for its surface must long continue to suffer aggradation before the lofty ranges around its depressed surface are worn down to its level. South Africa would seem to offer, according to the descriptions by Passarge, excellent opportunity for the successful advance of the arid cycle far into old age, because of the large extent of the land area, its sufficient height and inclosure, its long-undisturbed history, and its persistently arid climate.

It thus seems evident that the conditions necessary for desert-leveling are actually present in greater or less degree in different parts of the world.

The scheme of the arid cycle as an aid to observation.—The normal cycle has now been practically used by so many observers, and with so many advantageous results, that it is not unfair to expect similar advantage from the use of the arid cycle as an aid to observation in regions where it may be appropriately applied. Certain it is that many observations now on record with regard to arid regions do not suffice to indicate clearly the stage of erosion in the arid cycle there reached; and this, not because the observers had either reason or wish to dissent from the principles of the scheme, but because it was not consciously present in their minds when the observations were made. The same is often true of the scheme of the normal cycle. In both cases the failure of the observant explorer to refer the facts that he finds to some comprehensive scheme for their systematic treatment not only results in the accidental overlooking of certain significant facts and in the insufficient description of others, but it leaves the reader in great difficulty when he tries to visualize what the observer has seen. It is as if the writer and the reader had no common language in which the observations and thoughts of the one

should be transmitted to the other. It would be far otherwise if the description of a desert region were undertaken systematically in view of what seems to be the essential sequence of changes in all deserts; that is, if the mountains and basins, the rock plains and waste plains, the stream channels, the playas and the lakes, were all treated in view of their place in the cycle of changes through which they must be running. It is chiefly as an aid to observation and record, and as an aid to the understanding of observations thus recorded, that the scheme of the arid cycle may come to be of service.

It would be fitting to accompany an article of this kind with a larger number of actual examples than have been here introduced; but in the endeavor to find appropriate examples, the interpretation of the observations of various writers in view of the scheme here submitted has not seemed safe enough to make it worth while to undertake it. Safe interpretation needs the conscious application of the scheme by the observer in the field. When thus applied, it is to be hoped that the scheme of the arid cycle may lead to the detection of many facts concerning the evolution of land forms in desert regions that have thus far escaped notice. In the meantime, the scheme must remain in great part speculative.

The bearing of the arid cycle on theories of elevation and depression. —There is another aspect of the case which, to my mind, not only gives sufficient justification for all the speculation here presented, but makes one regret that it was not undertaken sooner; for in that case certain theoretical discussions would have earlier gained a firm foundation.

In a recent discussion of "The Bearing of Physiography on Suess' Theories" (*f*), I have urged that the occurrence of high-standing and isolated peneplains could not be the result of the depression of the surrounding lands—as is advocated by Suess—unless all the oceans and their associated lowlands on other continents were also depressed at the same time and by the same amount. The necessity of accepting world-wide crustal movements may, however, be avoided, if the high-standing truncated uplands are regarded as the result of local uplifts of formerly low-standing peneplains. This alternative conclusion is so simple and economical that it is accepted by many geologists and geographers; and it seems well based as long as one

believes that the even uplands can have been truncated only by peneplanation close to sea-level. As soon, however, as it is recognized that leveling may be accomplished in an arid region without baseleveling, it is no longer necessarily the case that truncated uplands represent uplifted peneplains; the uplands may perhaps be parts of ancient desert plains, originally denuded at their present altitude; and until this possibility is excluded, their isolated position may be explained by the depression of the surrounding lands, as Suess has supposed, without corresponding change in the level of the oceans and the other continents.

In the case of the truncated uplands or *horsts* of central Germany, there appears to be good geological reason for associating them with the denuded areas of the Ardennes and of Brittany, as described by Lapparent (*b*), and thus concluding that they were all low-lying peneplains before they were uplifted. In the case of the plateaus of northern Arizona, the evidence of normal peneplanation is less complete; yet, as above stated, it still seems probable that these plateaus were denuded with respect to normal baselevel, and that the canyon was cut across their surface in consequence of a later uplift with respect to sea-level. The Bural-bas-tau, a flat-topped range, and the associated plateau-like highlands in the Tian Shan system, also need reconsideration in view of the possibility of desert-leveling. I have treated the Bural-bas-tau (*e*, *f*, *g*), and Huntington has treated the associated highlands as uplifted peneplains. Friederichsen, on the other hand, while recognizing the highland region as a *Denudationsfläche*, has hesitated to treat it as a once low-lying peneplain, because of the possibility of its erosion above baselevel in a region of inland drainage. If such were the case, it need not have had that close relation to baselevel that is to be expected in a normal peneplain. Nevertheless, the truncated highlands and mountain tops in the Tian Shan seem to be closely related to the still low-lying plains of erosion that are drained by the Ili river to Lake Balkash, and also to the still lower-lying plain of erosion—apparently a true peneplain—that is drained by the Irtysh and the Ob to the Arctic ocean; hence the probability still seems great that the even highlands of the Bural-bas-tau represent a greatly uplifted plain, even though that plain may have been, at the time of its erosion,

a desert plain, and not a normal peneplain. It is therefore exceedingly improbable that the even-topped Bural-bas-tau, standing 12,000 or 13,000 feet above sea-level, gives any close measure of the altitude which the whole region possessed while the great erosion that it has suffered was accomplished.

LIST OF REFERENCES

BORNHARDT. "*Zur Oberflächengestaltung und Geologie Deutsch-Ostafrikas.*" (Berlin, 1900.)

DAVIS, W. M. (*a*) "Geographic Classification, Illustrated by a Study of Plains, Plateaus and Their Derivatives." *Proceedings of the American Association*, Vol. XXXIII (1884), pp. 428–32.

(*b*) "Geographic Methods in Geologic Investigation." *National Geographical Magazine*, Vol. I (1888), pp. 11–26.

(*c*) "The Geographical Cycle." *Geographical Journal* (London), Vol. XIV (1899), pp. 481–584.

(*d*) "Glacial Erosion in France, Switzerland and Norway." *Proceedings of the Boston Society of Natural History*, Vol. XXIX (1900), pp. 273-322.

(*e*) "A Flat-topped Range in the Tian Shan." *Appalachia*, Vol. X (1904), pp. 277–84.

(*f*) "The Bearing of Physiography on Suess' Theories." *American Journal of Science*, Vol. XIX (1905), pp. 265–73.

(*g*) "A Journey Across Turkestan." *Explorations in Turkestan* (Carnegie Institution Publications, No. 26, 1905), pp. 21–119.

(*h*) "The Complications of the Geographical Cycle." *Compte Rendu*, Eighth International Geographic Congress (In press.).

FRIEDERICHSEN, *Petermanns Mitteilungen*, Vol. XLIX, p. 136.

HUNTINGTON, E. "A Geologic and Physiographic Reconnaissance in Central Turkestan." *Explorations in Turkestan* (Carnegie Institution Publications, No. 26, 1905), pp. 157–216.

KEYES, C. R. "Geological Structure of New Mexican bolson Plains." *American Journal of Science*, Vol. XV (1903), pp. 207–10.

LAPPARENT, A. DE (*a*) *Leçons de géographie physique* (Paris, 1896).

(*b*) "La question de pénéplaines envisagée à la lumière des faits géologiques." *Verhandlungen des VII. Internationalen Geographischen Kongresses* (1899) (Berlin, 1901), Vol. II, pp. 213–20.

MCGEE, W J. "Sheetflood Erosion." *Bulletin of the Geological Society of America*, Vol. VIII (1897), pp. 87–112.

PASSARGE, S. (*a*) *Die Kalahari* (Berlin, 1904).

(*b*) "Rumpffläche und Inselberge." *Zeitschrift der deutschen geologischen Gesellschaft*, Vol. LVI (1904), Protokol, pp. 193–209.

(*c*) "Die Inselberglandschaften im tropischen Afrika." *Naturwiss. Wochenschr.*, new series, Vol. III (1904), 657–65.

PENCK, A. (*a*) "Einfluss des Klimas auf die Gestalt der Erdoberfläche." *Verhandlungen des III. deutschen Geographentages*, 1883, pp. 78–92.

(*b*) "Climatic Features in the Land Surface." *American Journal of Science*, Vol. XIX (1905), pp. 165–74.

WALTHER, J. *Das Gesetz der Wüstenbildung* (Berlin, 1900)